A Simple Design and Simulation of Full Bridge LLC Resonant DC-DC Converter for PV Applications

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**Abstract:** This paper deals with the design and simulation of full bridge LLC resonant converter suitable for photovoltaic applications. LLC converter has several desired features such as high efficiency, low electromagnetic interference (EMI) and high power density. This paper provides a detailed practical design aspect of full bridge LLC resonant converter. The LLC converter is implemented with a full-bridge on the primary side and a full-bridge rectifier on the secondary side. It includes designing the transformer turns ratio and selecting the components such as resonant inductor, resonant capacitor and magnetizing inductor. Also performance parameters such as voltage gain and output voltage ripple are calculated. Simulation of LLC resonant converter is carried out using MATLAB / SIMULINK and the results are verified.

**Key words:** LLC resonant converter • Output voltage ripple • Voltage gain

**INTRODUCTION**

The conventional Pulse Width Modulation (PWM) technique developed power by adjusting the duty cycle and interfering the power flow. Most the switching devices are hard-switched with sudden changes of currents and voltages, which results in more than a few switching losses and noises. In order to resolve the limitations of the conventional converters, the LLC resonant converter has been proposed. Basically the resonant technique process power in a sinusoid form and the switching devices are softly commutated [1-3]. Therefore the switching losses and noise can be theoretically reduced. Hence resonant converters have drawn a lot of attention in various applications [4]. It consists of two inductors and one capacitor and the converter can regulate the output voltage in contradiction of line and load variation over a wide range. The tank circuit of LLC Resonant Converter as shown in Fig. 1.

In LLC arrangement, the uncoupled inductor can be interchanged by a coupled one so that the size of the converter can be compact. This paper emphasis on the design features for the full bridge LLC resonant converter for photovoltaic applications. Beginning with a brief operation of basic full bridge LLC resonant converter is presented in Section II. Next, a method for defining parameter values is described in the form of flow chart and also to demonstrate how a design is created; a step-by-step procedure is presented for a converter with 500W of output power in Section III [5]. Simulation studies are carried out using MATLAB/SIMULINK. Finally performance parameters such as voltage gain and output voltage ripples are calculated.

**Operation of Full Bridge LLC Resonant DC-DC Converter:** Fig. 2 shows a typical topology of a full-bridge LLC resonant converter. The converter arrangement has three main parts. Such as switching bridge, LLC tank,
transformer and rectifier. Power switches Q1, Q2, Q3, Q4, which are generally MOSFETs, are arranged to form a square wave generator. This generator yields a bipolar square-wave voltage (Vsw) by driving switches Q1 and Q3 & Q2 and Q4, with alternating 50% duty cycles for each switch. A small dead time is needed between the successive transitions, both to avoid the possibility of cross conduction and to allow time for zero voltage switching (ZVS) to be attained. The resonant tank, also called a resonant network, consists of the resonant capacitance (Cr) and two inductances series resonant inductance (Lr) and the transformer’s magnetizing inductance (Lm). The transformer turns ratio is ‘n’. The resonant network circulates the electric current and as a result, the energy is circulated and delivered to the load through the transformer. The transformer’s primary winding accepts a bipolar square wave voltage. This voltage is transmitted to the secondary side, with the transformer given that both electrical isolation and the turn’s ratio to distribute the required voltage level to the output. On the converter’s secondary side, establish a full-bridge rectifier to convert AC input to DC output and supply the load R. The output capacitor smooth’s the rectified voltage and current [6].

For this configuration, there are two resonant frequencies. Resonant frequency one is determined by the resonant components Lr and Cr. The other one is determined by magnetizing inductance Lm, Cr and load condition. As load receiving heavier, the resonant frequency will shift to greater frequency. The two resonant frequencies are shown in equation 1 & 2.

\[
\begin{align*}
  f_{r1} &= \frac{1}{2\pi}\sqrt{\frac{L_r}{C_r}} \\
  f_{r2} &= \frac{1}{2\pi}\sqrt{\frac{L_m + L_r}{C_r}}
\end{align*}
\]

(1) 
(2)

The converter can function in three modes depending on Input voltage and load current conditions i.e. at resonance, below resonance and above resonance. Each of the modes pointed out may hold one or both of these operations [7].

- Power distribution operation happens twice in a switching cycle; first, when the resonant tank is Motivated with a positive voltage, current resonates in the positive way in the first half of the Switching cycle and second event is when the resonant tank is motivated with negative voltage, current resonates in the negative direction in the second half of the switching cycle, for the duration of the power distribution operations, the magnetizing inductor voltage is the positive/negative reflected output voltage and the magnetizing current is charging/discharging correspondingly. The difference between the resonant current and the magnetizing current permits through the transformer and rectifier to the secondary side and power is distributed to the load.

- Freewheeling operation happens following the power delivery operation only if the resonant Current extents the transformer magnetizing current, this only occurs when fss< fro, producing the transformer secondary current to reach zero and the secondary side rectifier to disconnect. Therefore the magnetizing inductor will be free to arrive the resonance with the resonant inductor and resonant capacitor, the frequency of this second resonance is smaller than the original resonant frequency fro, particularly at high values of m where Lm>>Lr, thus the primary current during the freewheeling operation will only changes lightly and can be estimated to be unchanged for simplicity.

**Design of LLC Resonant Converter:** Fig. 3 shows a design flow chart that reviews the design methodology of LLC resonant converter [8]. Initially the terminal voltages
Fig. 3: Design flow chart of LLC resonant converter

Vin_min, Vin_nom, & Vin_max must be taken from the converter Specifications. After that the transformer turns ratio (N) can be obtained from Equation 3 then the Mg_min and Mg_max, calculated using Equation 4 & 5. By selecting proper values for m and Q, the corresponding K_max value calculated. If it satisfies the desired condition then the designed converter should operate in the inductive region. Finally the resonant component values such as Cr, or and Lm are calculated using Equation 7, 8, 9 respectively.

The specifications for the design are:
Input voltage range: 18V–36V (33V_in_nom)
Output voltage: 270V
Maximum load: 145W

The design equations for turns ratio, resonant inductor, resonant capacitor, magnetizing inductor are as follows [9-11].

- Determine Transformer Turns Ratio (n)

The transformer turns ratio is determined by Equation 3.

\[
N_p / N_s = \left( \frac{V_{in\min}}{V_{out}} \right) M_{nom}
\]  

(3)

Here M_{nom} = 1

- Determine Mg_min and Mg_max

Mg_min And Mg_max can be determined by Equation 4 & 5

\[
M_{g_{\max}} = \left( \frac{V_{in\_{nom}}}{V_{in\_{max}}} \right) M_{nom}
\]  

(4)

\[
M_{g_{\min}} = \left( \frac{V_{in\_{nom}}}{V_{in\_{max}}} \right) M_{nom}
\]  

(5)

- Select m and Q_e

Moderate Q_e value of around 0.5 seems to be satisfying the voltage gain requirement.

Select Q_{max} moderately Q_e=0.4

Lower value of m can achieve higher boost gain, in addition to narrow range of frequency modulation.

Reasonable initial value for m=6.3

If the values m=6.3 and Q_e = 0.4 are selected, the corresponding K_{max}= 1.974, which is greater than M_{g_{\max}} = 1.833. No need for tuning the m value. Any K_{max} values above this line are greater than M_{g_{\max}}. So the designed converter should operate in the inductive region. Which satisfies the design requirement?

- Calculating resonant component values

The reflected load resistance at full load is calculated by Equation 6.

\[
R_{ac\min} = \frac{8}{\pi^2} \times \left( \frac{N_f^2}{N_i^2} \right) \frac{V_{out}^2}{P_{in\max}}
\]  

(6)

Next we solve the Equations 7, 8, 9 to obtain the resonant tank component values.

\[
Q_{max} = 0.4 = \frac{\sqrt{L_r}}{\frac{R_{ac\min}}{\sqrt{C_r}}}
\]  

(7)

\[
f_r = 100 KHz = \frac{1}{2\pi\sqrt{L_r C_r}}
\]  

(8)
Table 1: Design Equations

<table>
<thead>
<tr>
<th>Normalized Gain</th>
<th>Resonant Frequency</th>
<th>Quality Factor</th>
<th>Normalized Frequency</th>
<th>Inductor Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M = \frac{V_{in} - nom}{V_{in} - min} \times M_{nom} )</td>
<td>( f_r = \frac{1}{2\pi \sqrt{L_r \cdot C_r}} )</td>
<td>( Q_{max} = \sqrt{\frac{L_r}{R_{ac - min}}} )</td>
<td>( f_s = f_r )</td>
<td>( m = \frac{L_r + L_m}{L_r} )</td>
</tr>
</tbody>
</table>

Table 2: Voltage and Current Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage ( V_{in} )</td>
<td>33V</td>
</tr>
<tr>
<td>Output Voltage ( V_o )</td>
<td>270V</td>
</tr>
<tr>
<td>Output Current ( I_o )</td>
<td>1.85A</td>
</tr>
<tr>
<td>Output Power ( P_o )</td>
<td>500W</td>
</tr>
</tbody>
</table>

Table 3: Design Parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Designator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Inductor</td>
<td>( L_m )</td>
<td>5.95( \mu )H</td>
</tr>
<tr>
<td>Resonant Inductor</td>
<td>( L_r )</td>
<td>1.1238( \mu )H</td>
</tr>
<tr>
<td>Resonant Capacitor</td>
<td>( C_r )</td>
<td>2.25( \mu )H</td>
</tr>
<tr>
<td>Duty Ratio</td>
<td>( D )</td>
<td>0.5</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>( f_s )</td>
<td>48.9Khz</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>( N )</td>
<td>1:12.12</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>( f_r )</td>
<td>100Khz</td>
</tr>
<tr>
<td>Reflected load resistance</td>
<td>( R_{ac - min} )</td>
<td>1.763( \Omega )</td>
</tr>
</tbody>
</table>

\[ m = 6.3 = \frac{L_r + L_m}{L_r} \quad (9) \]

\[ L_r = 1.1238\( \mu \)H, \quad L_m = 5.95\( \mu \)H, \quad C_r = 2.25\( \mu \)H \]

Specifications of the 500W LLC resonant converter are as follows:

RESULTS

Simulation studies are carried out using MATLAB/SIMULINK and the simulation circuit of full bridge LLC Resonant DC-DC Converter for an input of 33V is shown in Fig. 4.

The driving pulse of MOSFET Q1&Q3 with phase delay of 0 and duty ratio of 0.5 is obtained. Driving pulse of MOSFET Q1&Q3, current and voltage waveforms are as shown in Fig. 5.

The driving pulse of MOSFET Q2&Q4 with phase delay of 180° and duty ratio of 0.5 is obtained. Driving pulse of MOSFET Q2&Q4, current and voltage waveforms are as shown in Fig. 6.

Output voltage of inverter and Current through Resonant components is as shown in Fig. 7 (a) & (b) Fig. 8 (a) & (b) shows the simulated voltage waveforms resultant to the primary side & secondary side of the transformer which are achieved by experiments of the 500W converter under normal load Condition.

Fig. 4: Simulink diagram of full bridge LLC resonant converter
Fig. 5: Driving pulse of MOSFET Q1&Q3, current and voltage waveforms

Fig. 6: Driving pulse of MOSFET Q2&Q4, current and voltage waveforms

Fig. 7: Output voltage of inverter & current through resonant components
Fig. 8: Transformer primary and secondary voltages

Fig. 9: Output current, output voltage and output power of LLC resonant converter

Output ripple voltage of LLC Resonant Converter

Fig. 10: Output ripple voltage waveform

Table 4: Performance Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Full bridge LLC resonant converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage gain</td>
<td>1.833</td>
</tr>
<tr>
<td>Output voltage ripple</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Fig. 9 (a), (b), (c) shows the simulation results of output current, output voltage and output power of LLC converter under normal load conditions. It is observed that soft-commutation of both output diodes and power MOSFET’s are achieved. So that simulated output power is near to the estimated value with the input voltage of 33V.

**Evaluation of Performance Parameters for LLC Converter:** The performance of full bridge LLC resonant converter is examined by calculating the voltage gain and output voltage ripple by using the equation 10, 11.

\[
M_{\text{max}} = \frac{V_{\text{in}} - \text{nom}}{V_{\text{in}} - \text{min}} \times M_{\text{nom}}
\]

The Ripple in the output voltage is calculated as.

\[
V_{\text{ripple}} = \frac{V_{\text{max}} - V_{\text{min}}}{\text{vavg}}
\]

where \(V_{\text{avg}}\) as the average value of maximum and minimum voltage from voltage ripple waveform [12]. The output voltage ripple waveform as shown in Fig. 10 and it is around 0.003. Table 4 shows performance parameter of LLC resonant converter.

**CONCLUSION**

The design procedure of Full Bridge LLC Resonant Converter is presented for photovoltaic application. Theoretical values of resonant component values are calculated using the design equations. Simulation results are provided for LLC Resonant converter for an input voltage of 33V. The voltage gain and output voltage ripple of LLC resonant converter is calculated which shows that the ripple is less in the proposed converter.

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**REFERENCES**


